Evaluation of Metro Kapsul Performance in Steady State Curving, Traction, and Braking

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Abstract. Transportation is an important life aspect to save travel time from one place to another. However, traffic congestion is a major problem. Therefore, PT TReKKa intends to develop Metro Kapsul, a mass public transportation system that is suitable for densely populated developed cities. A series of technical analyses and evaluations is necessary to ensure vehicle safety in steady-state curving, traction, and braking. The maximum velocity and acceleration/deceleration in these conditions can be used to decide the development and manufacturing process of Metro Kapsul. The analyses consisted of theoretical and numerical simulations. The theoretical analysis involved applying force equilibrium condition of a rigid body. The simulation was modeled according to a real model of Metro Kapsul. The results showed that both values could be categorized as comfortable based on ASCE 21.2-2008. From this study, the safe longitudinal acceleration and deceleration of Metro Kapsul were obtained, i.e. 0.90 m/s^2 and 0.97 m/s^2, respectively, while the emergency longitudinal deceleration is 1.25 m/s^2. When cornering, the maximum velocity is limited by the centrifugal acceleration, which is 0.6 m/s^2. To conclude, the current design of Metro Kapsul is already good in steady-state performance. Further research is required for full dynamic and transient conditions with track irregularities.

Keywords: *braking; curving; Metro Kapsul; steady state; traction.*

1 Introduction

Modern transportation is an important aspect of life, especially for urban communities with high mobility. It saves time to travel from one place to another. However, the high population combined with a high growth rate will cause major problems in modern transportation in crowded urban areas in the form of traffic jams. Indonesia has a population of 237.6 million people [1], with a population growth rate of 1.36% per year from 2010 to 2016 [2]. A high population leads to an increase the number of vehicles. This will make the streets more crowded and will certainly make travel time longer. Solutions are

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needed to overcome these problems; one is the development of mass public transportation.

Several urban mass public transportation solutions already exist, such as Mass Rapid Transit (MRT), Light Rail Transit (LRT), and subways. However, there is still room to improve these existing systems. Currently, an unmanned control system, the so-called Automated People Mover, Metro Kapsul, is being developed by PT TReKKa. It has two bogies, each have four wheels with rubber tires and two sets of guidewheels. The Metro Kapsul uses an elevated track.

The Metro Kapsul is smaller than other forms of mass public transportation. It was designed to operate each individual 'Kapsul' automatically. The system is planned to operate in Bandung City first and probably is the best available solution for crowded places with a compact layout such as Bandung. The development cost is also much lower than that of MRT, LRT, and subways. A photograph of the prototype is shown in Figure 1. Until now, it has been operated in the Subang area for trial and development.

Figure 1 Metro Kapsul protoype in Subang.

It is expected to become a mass transportation option that will save travel time, especially in developed cities. However, before it can operate, a series of technical analyses and evaluations is necessary to ensure its feasibility and safety, including its performance in steady state curving, traction, and braking.

When the Metro Kapsul curves at a certain speed and at a certain radius, centrifugal force is applied to its body. This centrifugal force makes the vehicle tend to roll or shift to the outer curve. Hence, the maximum speed should be determined to ensure it will not roll or shift to the outer curve. This also applies when the Metro Kapsul accelerates and decelerates, especially when it goes downhill or uphill. The acceleration/deceleration of Metro Kapsul causes an inertia force on its body, which can make the vehicle pitch; either front or back pitching, depending on whether it accelerates or decelerates. This endangers the safety of passengers. Therefore, the maximum acceleration and deceleration should be determined for a specified longitudinal road slope.

The results of this work will be given to PT TReKKa and the authors hope that this work will help them to decide further steps in Metro Kapsul's development. The results can be used as the basis to determine the specifications of the track, the operating speed and the acceleration/deceleration of the Metro Kapsul, or whether the design should be improved or not.

In terms of performance evaluation of the Metro Kapsul, this paper discusses quasi-static conditions only. In further research, a full dynamic and transient analysis of the latest design on a track with irregularities may be considered.

2 Methodology

The analysis in this paper is divided into two approaches: a theoretical analysis and a simulation. The theoretical analysis refers to Budiwantoro's paper [3], which investigated the stability of a rail conveyor vehicle. Rail conveyor vehicles use rail wheels and rails, which is different from the Metro Kapsul, which uses rubber tires on a concrete track. The theoretical analysis in this research was done by modeling the Metro Kapsul as a rigid body, similar to the approach previously used in Ref. [3]. A rigid body model was used because it has a simpler and more conservative calculation compared to the modeling that includes a flexible body with suspension. The authors used a multi-body system software called SIMPACK for the simulation. The Metro Kapsul was modeled according to the latest design of the Metro Kapsul, including suspension, dampers and other components, to represent the actual components used in the Metro Kapsul.

The analysis concerned five cases: front pitching, back pitching, rolling, shifting to outer curve and shifting to inner curve. This research used the ASCE 21.2-08 standard [4], a standard for Automated People Movers (APM). According to the definition of an APM in the standard, the Metro Kapsul is a type of APM. Three load cases are defined in the standard, i.e. AW0, AW1, and AW2. AW0 is the empty weight of the vehicle. AW1 is the empty weight of the vehicle plus the design capacity of the vehicle. AW2 is the empty weight of the vehicle plus the maximum capacity of the vehicle.

The analysis required data of the Metro Kapsul's mass, the center of gravity, the moment of inertia, the dimensions, and its components, along with the damper and spring coefficient of the suspension. All data were taken for the latest prototype developed by the company. Some data were collected directly from the company, while other data were obtained from software calculation and other references. For instance, the mass of the Metro Kapsul was obtained from Febrianto [5] and Masduqi [6]. Meanwhile, the inertia moment data were calculated automatically in the SIMPACK software application. From the collected data, a theoretical analysis was conducted by applying Newton's Law in equilibrium state for a number of conditions, such as rolling, pitching, and shifting from the track, which were also used for the model simulation developed in SIMPACK. Thereafter, both results were compared with the comfort criteria from ASCE 21.2-08. The criteria are shown in Table 1.

Table 1 Comfort criteria.

Direction	Standing	Sitting
Lateral	±0.1 g	±.0.25 g
Vertical	±0.05 g	±0.25 g
Longitudinal (Normal)	±0.16 g	±0.35 g
Longitudinal (Emergency)	±.0.32 g	±0.60 g

Source: ANSI/ASCE/T&DI 21.2-08

The front pitching case determined the maximum deceleration, the back pitching case determined the maximum acceleration, the rolling case and shifting to outer curve case determined the maximum velocity when turning, and the shifting to the inner curve determined the minimum velocity when turning.

3 Data

Most data for this research were collected from the company. The data included the specifications, dimensions, and mass of the Metro Kapsul. The specifications and dimensions were obtained from the company's documentation [7-8]. Meanwhile, the mass data were obtained from Febrianto [5] and Masduqi [6]. As for the center of gravity, the data were obtained from a 3D drawing. As mentioned before, the inert moment data were automatically calculated by the SIMPACK software application. The data are shown in Tables 2 to 5.

Table 2 Dimensions of Metro Kapsul.

Dimension	Value	Unit
Length of body	9,300	mm
Height of body	3,100	mm
Width of body	2,550	mm
Track width	1,600	mm
Total height	4,500	mm
Distance between bogies	5,010	mm
Wheel diameter	900	mm
Guide track width	840	mm

Source: PT TReKKa [7-8]

Table 3 Specifications of Metro Kapsul.

Parameter	Value	Unit
Operational velocity	40	km/h
Maximum velocity	80	km/h
Maximum slope	5	%
Maximum acceleration	3,25	km/h/s
Maximum deceleration (operation)	3,5	km/h/s
Maximum deceleration (emergency)	4,5	km/h/s
Minimum curve radius	15	m
Capacity	50	Persons

Source: PT TReKKa [7-8]

Table 4 Mass components [5-6].

Component	Mass <kg>
Body frame	498
Floor, skin, interior	452
Base frame	686
Bogie	2 x 841.58
Utilities	336

Table 5 Mass utilities [5].

Utilities	Mass <kg>
Air conditioner	2 x 30
Battery	140
Connector A	10
Connector B	10
Connector C	10
Air tank	2 x 20
Compressor	16
Others	50

Another data is the friction coefficient, which was collected from engineeringtoolbox.com [9]. For a conservative application the lowest value of friction coefficient was used, i.e. 0.45.

4 Theoretical Analysis

The theoretical analysis was done by applying Newton's Law in steady state equilibrium condition. It was assumed that the whole body of the Metro Kapsul was rigid, which means there is no deflection of the body. As explained before, five cases were considered in this analysis: front pitching, back pitching, rolling, shifting to outer curve and shifting to inner curve.

4.1 Front pitching

Front pitching occurs when the Metro Kapsul decelerates or brakes at a certain value (a_x). A free body diagram is shown in Figure 2.

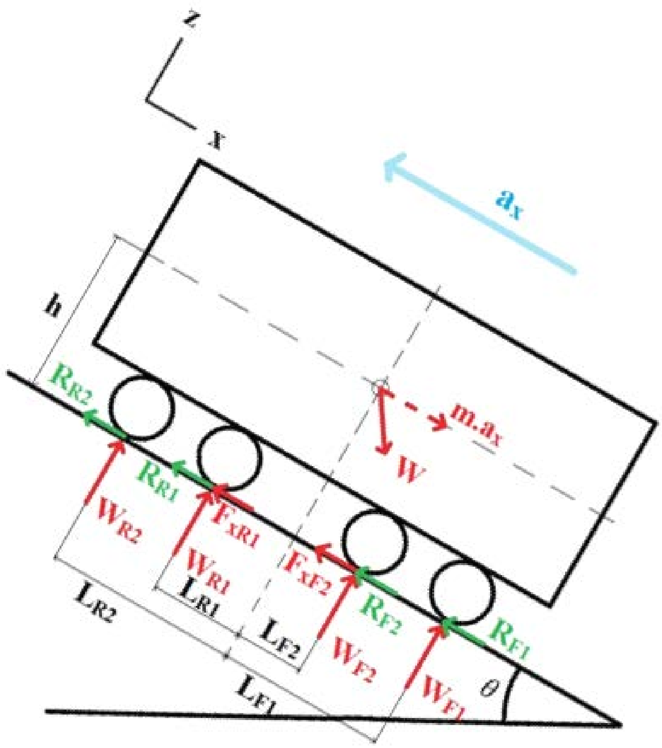

Figure 2 Front pitching free body diagram.

In this condition, the Metro Kapsul is moving downward on a track with a slope of θ. One portion of its weight (*W*) will keep all tires of the Metro Kapsul ($W_{F1}, W_{F2}, W_{R1}, W_{R2}$) in contact with the road surface, while the other portion will make it pitch.

The weight acts at the center of gravity of the Metro Kapsul, at height h from the road surface. Braking is done by four inner wheels (F_{xF2}, F_{xR1}) and there is also rolling resistance on all wheels, indicated by R_{F1}, R_{F2}, R_{R1}, and R_{R2}. Front pitching will occur when $W_{F2} = W_{R1} = W_{R2} = 0$. From the force and moment analysis, the maximum deceleration is:

$$a_x = \frac{g}{h}(L_{F1} \cos\theta - h \sin\theta) \tag{1}$$

where *g* is the gravitational acceleration.

4.2 Back Pitching

Back pitching occurs when the Metro Kapsul accelerates at a certain value (a_x). A free body diagram is shown in Figure 3.

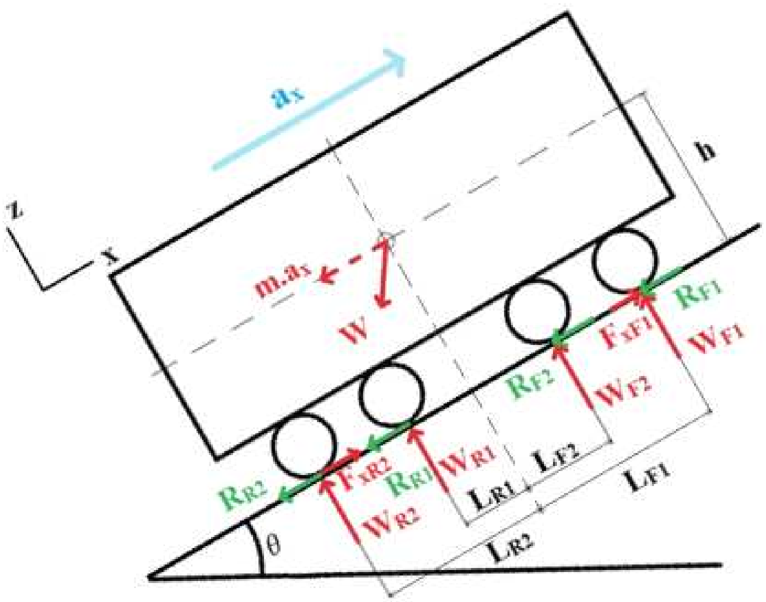

Figure 3 Back Pitching free body diagram.

In this condition, the Metro Kapsul is going upward on a track with a slope of θ. The entire symbol is the same as in the front pitching case, except there is no braking force and there is traction on the four outer wheels (F_{X1}, F_{R2}). Back pitching will occur when $W_{F1} = W_{F2} = W_{R1} = 0$ From the force and moment analysis, the maximum acceleration is:

$$a_x = \frac{g}{h}(L_{R2} \cos\theta - h \sin\theta) \qquad (2)$$

4.3 Rolling

Rolling will occur when the Metro Kapsul turns at a certain radius (R) at a certain acceleration (a_x). The free body diagram is shown in Figure 4.

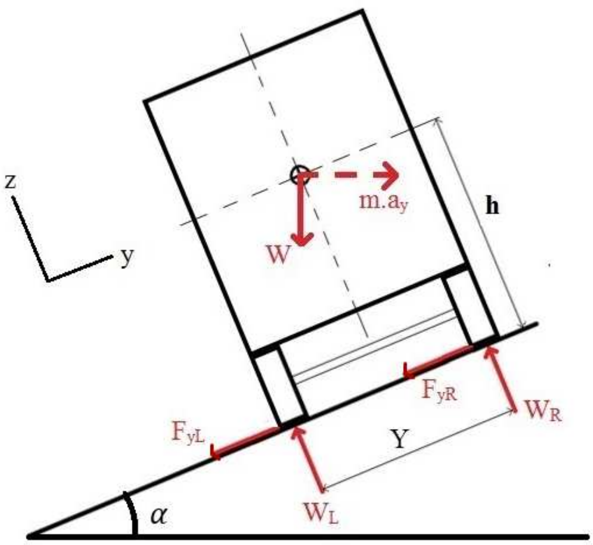

Figure 4 Rolling free body diagram.

The weight (W) will keep all tires of the Metro Kapsul (W_L, W_R) in contact with the road surface and another part makes it tend to roll. The weight acts at the center of gravity of the Metro Kapsul at height h from the road surface. F_{yL} and F_{yR} are the friction forces of the tires and Y is the distance between the left and the right wheel. Rolling will occur when $W_R = 0$. From the force and moment analysis, the maximum centrifugal and maximum turning velocity before rolling is:

$$a_x = g\frac{h \sin\alpha + 0{,}5\, Y \cos\alpha}{h \cos\alpha + 0{,}5 Y \sin\alpha} \qquad (3)$$

$$V_{max} = \sqrt{a_y R} \quad (4)$$

4.4 Shifting to Outer Curve

The shifting cases are similar to the rolling case. Shifting occurs when the Metro Kapsul turns at a certain radius (R) with a certain acceleration. Shifting tends to occur more when the coefficient friction between the tires and the road surface is small, so it usually happens on wet roads or a snowy path. A free body diagram is shown in Figure 5.

The entire symbol is the same as in the rolling case, except the friction forces are now indicated by f_L and f_R. The friction force value is a product of the friction coefficient (μ_s) and the normal forces.

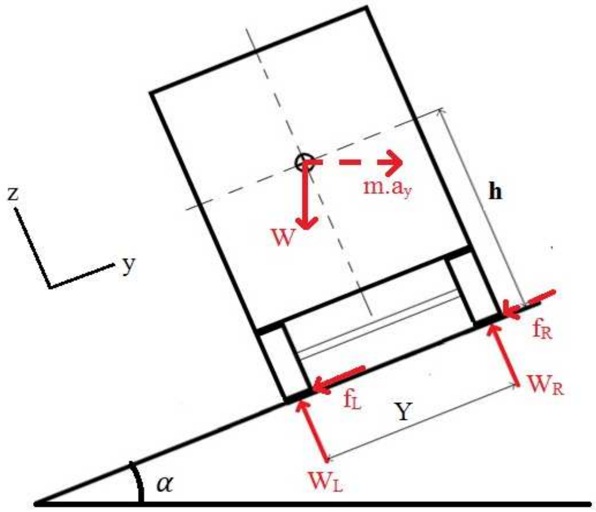

Figure 5 Shifting to outer curve free body diagram.

From the force and moment analysis, the maximum centrifugal and maximum turning velocity before shifting are:

$$a_x = g\,\frac{\sin\alpha + \mu_S \cos\alpha}{\cos\alpha - \mu_S \sin\alpha} \quad (5)$$

$$V_{max} = \sqrt{a_y R} \quad (6)$$

4.5 Shifting to Inner Curve

This case is the opposite of the shifting to outer curve case. It determines the minimum velocity, V_{min} of the Metro Kapsul before it shifts. A free body diagram is shown in Figure 6.

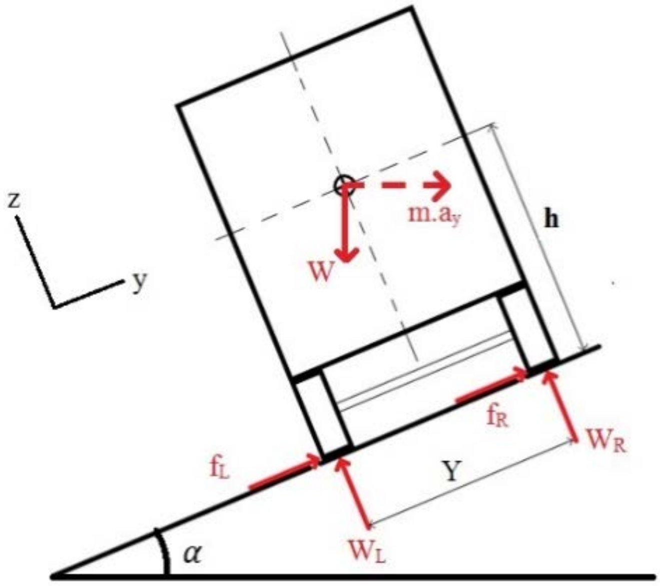

Figure 6 Shifting to inner curve free body diagram.

All the symbols are the same as in the previous case. From the force and moment analysis, the maximum centrifugal and maximum turning velocity before shifting are:

$$a_y = g\frac{\sin\alpha - \mu_S\cos\alpha}{\mu_S\sin\alpha + \cos\alpha} \quad (7)$$

$$V_{min} = \sqrt{a_y R} \quad (8)$$

5 Model, Validation, and Simulation

The 3D model of Metro Kapsul and its bogie made in SIMPACK are shown in Figures 7 and 8.

The model consists of a body and two bogies. Schematics of the 2D model are shown in Figures 9 and 10. The red lines indicate force elements that connect both bodies, the green lines indicate constraints, and the blue lines indicate the joints between the bodies. Figure 10 shows the wheel and steering system in the 2D model shown in Figure 9. The wheel and steering systems in Figure 9 each have the model shown in Figure 10. Validation is based on two parameters: the normal force and the lateral force on the wheels.

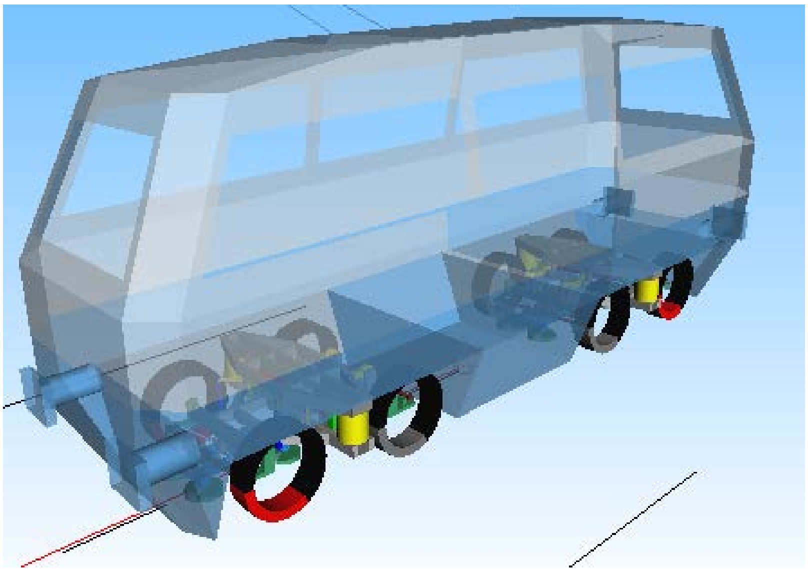

Figure 7 Metro Kapsul model.

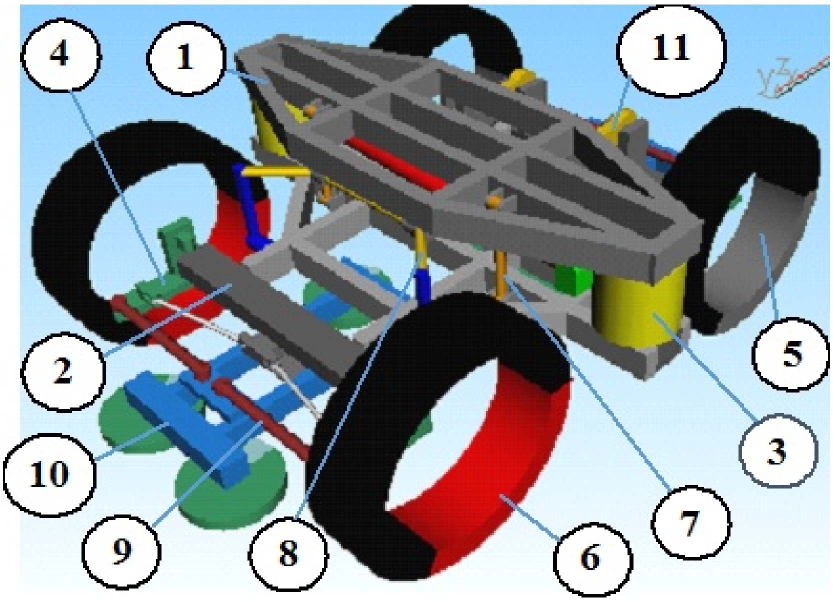

Figure 8 Bogie model: 1) bolster, 2) bogie frame, 3) air spring, 4) wheel plate, 5) brake wheel, 6) motor wheel, 7) damper, 8) antiroll bar, 9) steering, 10) guidewheel set, 11) stock axle.

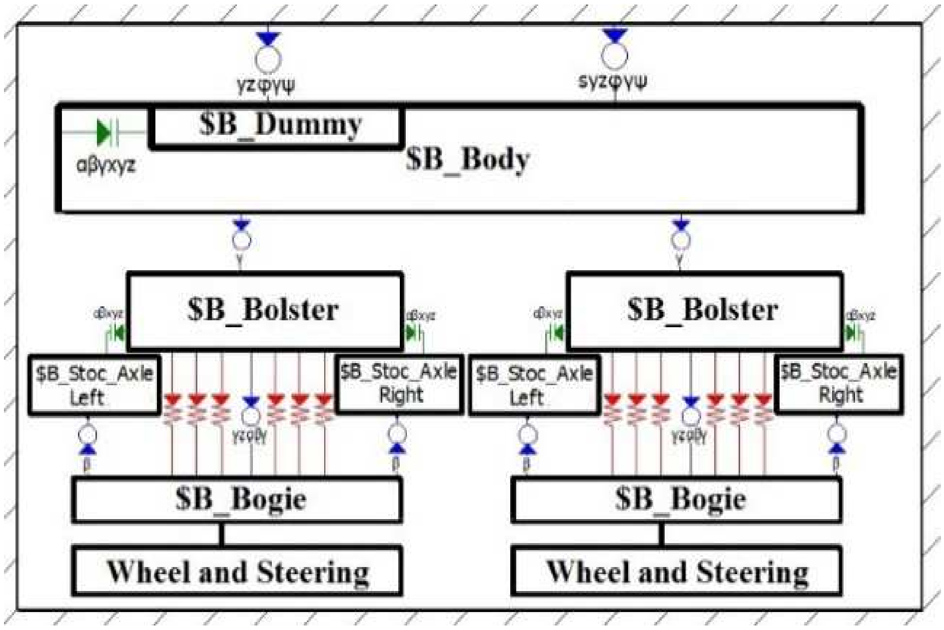

Figure 9 2D-model of the Metro Kapsul.

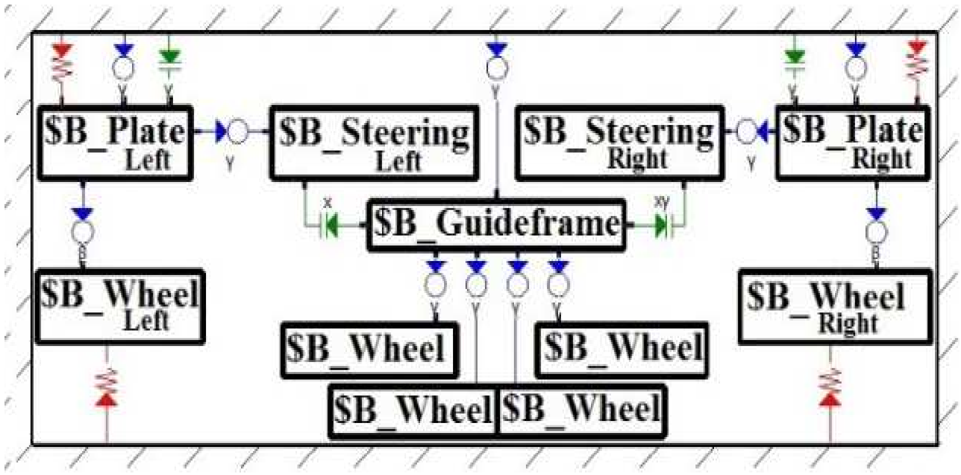

Figure 10 2D-model of the wheel and steering system.

Table 6 shows the normal forces of the Metro Kapsul's wheels and Table 7 shows the lateral forces. The error is less than 1.4%, therefore the model is valid.

Table 6 Normal forces of Metro Kapsul from simulation.

Wheel		Normal force <N>	
		Straight	**Turning**
Front bogie	Front left	8,529.90	6,404.46
	Front right	9,302.82	11,237.80
	Rear left	8,571.51	6,911.85
	Rear right	9,343.55	11,753.10
Rear bogie	Front left	8,503.62	6,367.02
	Front right	9,334.69	11,276.60
	Rear left	8,499.47	6,269.99
	Rear right	9,374.64	11,233.60
Total		71,459.24	71,454.42
Theoretical		72,438.02	72,438.02
Error		**1.35%**	**1.36%**

Table 7 Centrifugal force of Metro Kapsul from simulation.

Wheel		Centrifugal Force <N>
Front bogie	Front left	952.50
	Front right	1,250.07
	Rear left	787.99
	Rear right	654.45
Rear bogie	Front left	4,089.48
	Front right	5,918.06
	Rear left	−1,436.55
	Rear right	−934.70
Total		11,281.30
Theoretical		11,395.22
Error		0,99%

Then, the simulation was conducted based on the cases and loads that have been explained in Section 2 (Methodology).

6 Results and Discussion

There are slight differences between the theoretical results and the simulation results, where the theoretical results are higher. For all cases, the acceleration values were much higher than the values from the ASCE comfort criteria. The results for front and back pitching are shown in Figures 11 and 12. From Figure 11, the maximum deceleration based on the safety and comfort criteria is 1.57 m/s^2 for normal operation and 3.14 m/s^2 for emergency. For a conservative application, the maximum deceleration taken is 0.97 m/s^2 for normal operation and 1.25 m/s^2 for an emergency. These values come from the company's design process.

Figure 12 shows the results for the back pitching case. From the graph, the maximum acceleration for normal and emergency operation are the same as in the front pitching case. This is because the values come from ASCE's comfort criteria. Therefore, the maximum acceleration from the specification is below this number, so the value taken is 0.90 m/s^2.

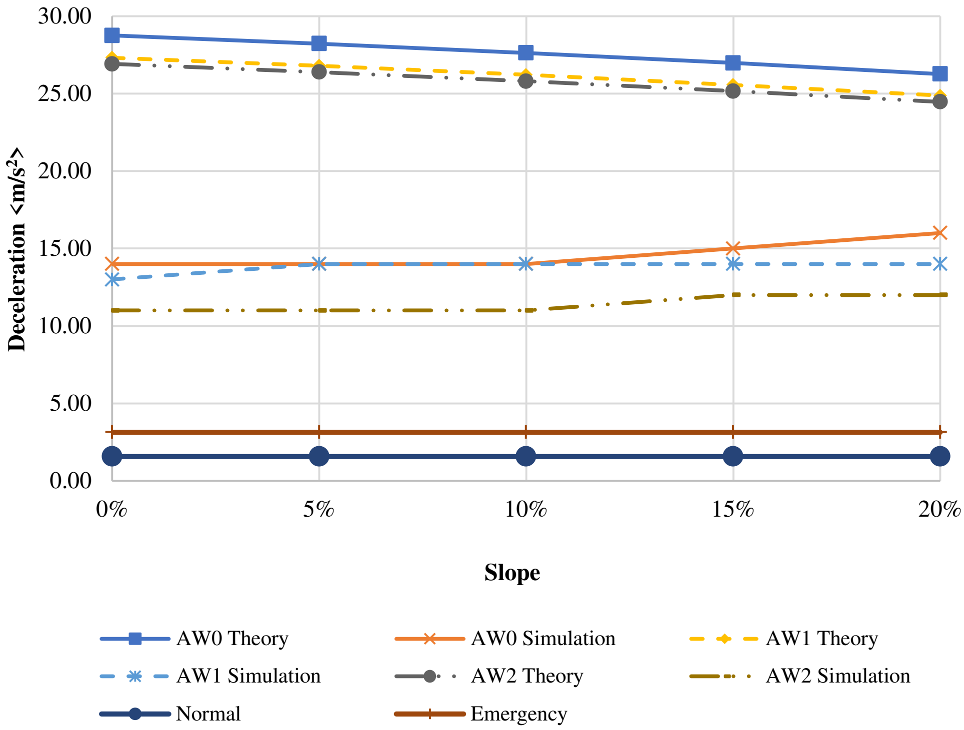

Figure 11 Front pitching results: deceleration vs slope.

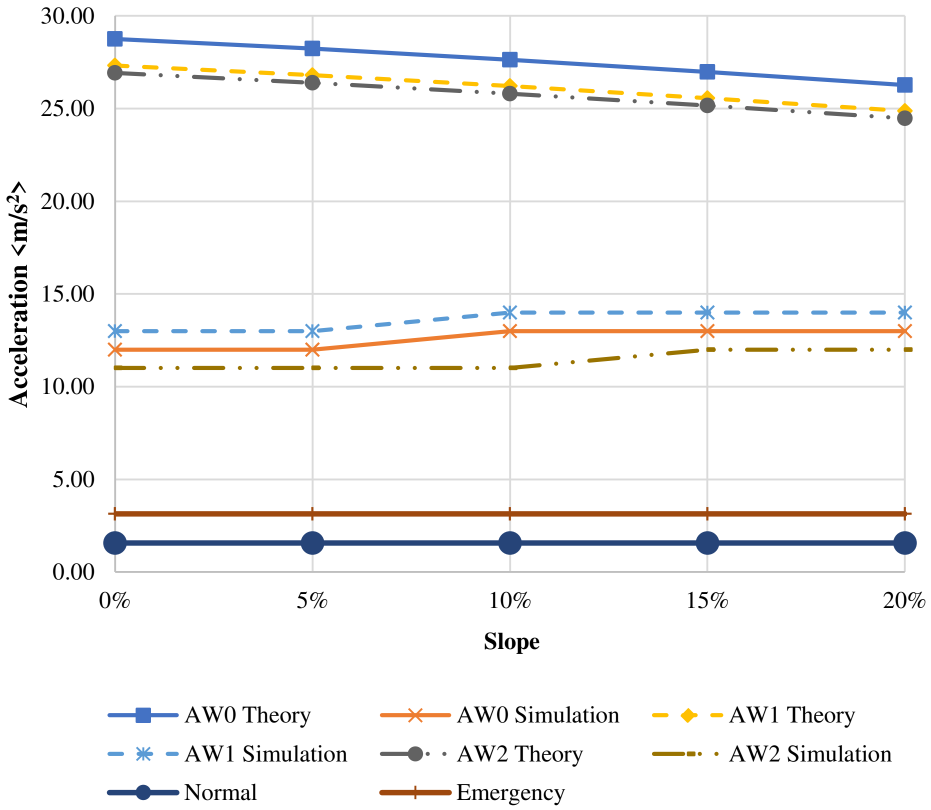

Figure 12 Back pitching results: acceleration vs slope.

The results for the rolling case with a load of AW0 are shown in Figures 13 and 14. The graphs show that a higher radius will make the maximum turning velocity higher. The reason is that a higher radius will make the centrifugal force applied to the Metro Kapsul decrease. A higher lateral velocity will also increase the Metro Kapsul's maximum turning velocity because some of the weight will help to resist the roll moment.

The graphs for AW1 and AW2 are similar to AW0. The maximum turning velocity for all load cases is shown in Table 8. The maximum turning velocity permitted for the Metro Kapsul at a radius of 80 meters is 77 km/h for AW0, 73 km/h for AW1, and 72 km/h for AW2. From these results, it can be concluded that as the load increases, the maximum turning velocity will increase too. This happens because if more passengers ride the Metro Kapsul, the overall center of gravity will be higher. Therefore, the Metro Kapsul will more easily roll over.

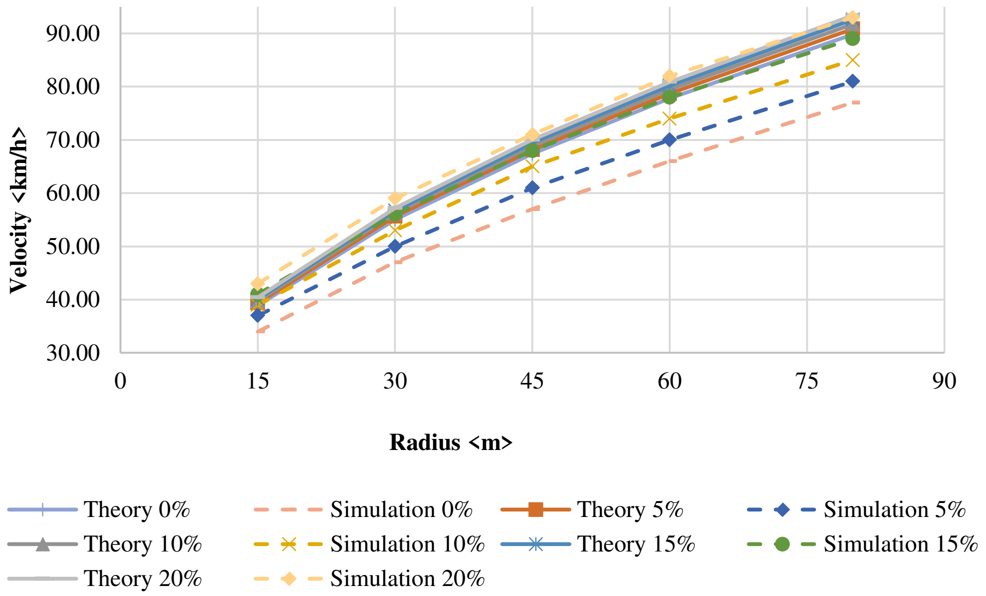

Figure 13 Rolling case results for AW0: velocity vs radius.

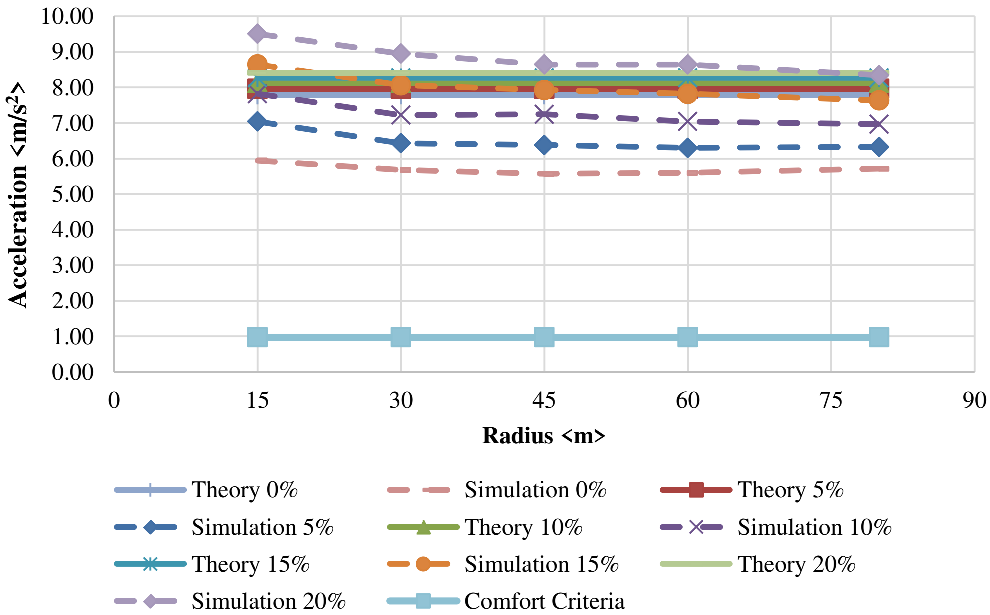

Figure 14 Rolling case results for AW0: acceleration vs radius.

Table 8 Maximum turning velocity results for rolling case.

Radius <m>	**AW0**	**AW1**	**AW2**
	Velocity <km/h>	**Velocity <km/h>**	**Velocity <km/h>**
15	34	33	32
30	47	46	44
45	57	56	55
60	66	64	61
80	77	73	72

The maximum lateral or centrifugal acceleration for the rolling case are shown in Table 9. As can be seen from this table, the results are all higher than the lateral acceleration from ASCE's comfort criteria. Hence, the maximum acceleration value is lower than that number, i.e. 0.98 meters per square second.

Table 9 Maximum centrifugal acceleration results for rolling case.

Radius <m>	**AW0**	**AW1**	**AW2**
	Acceleration <m/s^2>	**Acceleration <m/s^2>**	**Acceleration <m/s^2>**
15	5.95	5.6	5.27
30	5.68	5.44	4.98
45	5.57	5.38	5.19
60	5.60	5.27	4.79
80	5.72	5.14	5.00

Figures 15 and 16 show the results for shifting to the outer curve cases with a load of AW0.

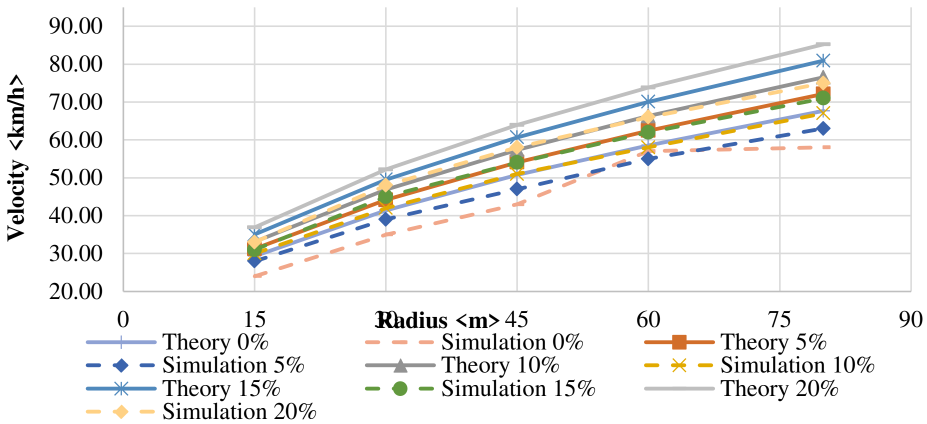

Figure 15 Shifting to the outer curve case results for AW0: velocity vs radius.

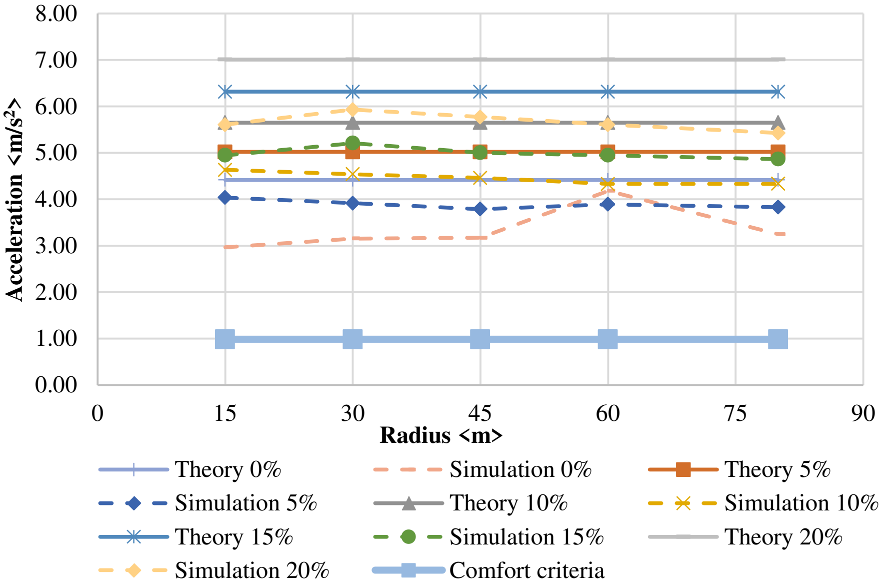

Figure 16 Shifting to the outer curve case results for AW0: acceleration vs radius.

The tendency is the same as in the rolling case, where a higher radius and slope will increase the maximum turning velocity. Table 10 shows the maximum turning velocity before shifting.

Table 10 Maximum turning velocity results for shifting to outer curve case.

Radius <m>	**AW0**	**AW1**	**AW2**
	Velocity <km/h>	**Velocity <km/h>**	**Velocity <km/h>**
15	24	24	23
30	35	35	37
45	43	43	42
60	57	50	48
80	58	57	55

The results for a radius of 80 meters were 58 km/h for AW0, 57 km/h for AW1, and 55 km/h for AW2. Compared with Table 8 these results are lower. This means that the Metro Kapsul will shift to the outer curve first when the track surface is wet.

Table 11 shows the maximum lateral or centrifugal acceleration before the Metro Kapsul will shift to the outer curve.

Table 11 Maximum centrifugal acceleration results for shifting to outer curve case.

Radius <m>	AW0	AW1	AW2
	Acceleration <m/s^2>	Acceleration <m/s^2>	Acceleration <m/s^2>
15	2.96	2.96	2.72
30	3.15	3.15	3.52
45	3.17	3.17	3.02
60	4.18	3.22	2.96
80	3.24	3.13	2.92

The same as in the rolling case, the results are higher than the lateral acceleration from ASCE's comfort criteria. Hence, the lowest value for the maximum acceleration is 0.98 m/s^2.

From the rolling and shifting to the outer curve cases, the maximum centrifugal acceleration is 0.98 m/s^2 as in ASCE's comfort criteria. Therefore, for a conservative application the maximum centrifugal acceleration taken is 0.6 m/s^2. From the acceleration value, the maximum turning velocity can be determined. Table 12 shows the maximum turning velocity for the Metro Kapsul at several radii.

Table 12 Maximum turning velocity at several Radii.

Radius (Meter)	Velocity (Kilometer per hour)
15	10.80
30	15.27
56	19.71
60	21.60
80	24.94

The results of the shifting to the inner curve case are shown in Table 13.

Table 13 Shifting to inner curve case results for all loads.

Slope	Theory	*Simulation
5%	0 km/h	3 km/h
10%	0 km/h	3 km/h
15%	0 km/h	3 km/h
20%	0 km/h	3 km/h

*Due to software constraints

The cases were conducted using a radius of 15 meters. The results indicate that, theoretically, the Metro Kapsul will not shift to the inner curve until the lateral slope reaches 45%. The slope of the vehicle will not reach 45%. Therefore, there is no minimum velocity or minimum lateral acceleration for the Metro Kapsul when turning.

The five cases discussed before provide results for quasi-static conditions. This study did not include measurements for a full dynamic/transient analysis with the latest design of the Metro Kapsul, but they have been made for the first prototype in a previous work [10] on a closed-loop track in Subang. Testing was done when the prototype had gone through one full path of the track, using an accelerometer to measure the acceleration at three positions: front, center, and rear body of the Metro Kapsul.

The results were stated in the resultant RMS acceleration. The values were 0.602 m/s^2 on the front body, 0.534 m/s^2 on the center body, and 0.617 m/s^2 on the rear body. ISO 2631 is a standard for mechanical vibration and shock. Based on the comfort categories in this standard, all the measured values belong to the category 'fairly uncomfortable'. This is probably because of an inadequate suspension system. If the results are plotted into a fatigue-decreased proficiency boundaries graph, the passengers will not be able to withstand the Metro Kapsul for more than 25 minutes in longitudinal direction and one minute for lateral and vertical directions. Hence, it is important to do a stability analysis of the full dynamic/transient system for the Metro Kapsul.

7 Conclusions

In normal operations, the longitudinal acceleration of the Metro Kapsul is 0.90 m/s^2 and the longitudinal deceleration is 0.97 m/s^2. In emergency situations, longitudinal deceleration should be 1.25 m/s^2. When cornering, the maximum velocity is limited by centrifugal acceleration, which is 0.6 m/s^2. This paper only discussed the stability performance of the Metro Kapsul in quasi-static condition. For further research, full dynamic/transient analysis can be done by analyzing the stability with the latest design of the Metro Kapsul on a track with irregularities.

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